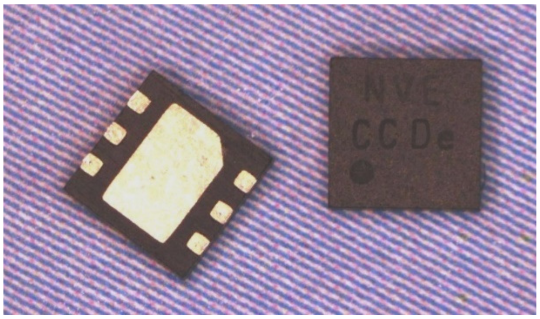
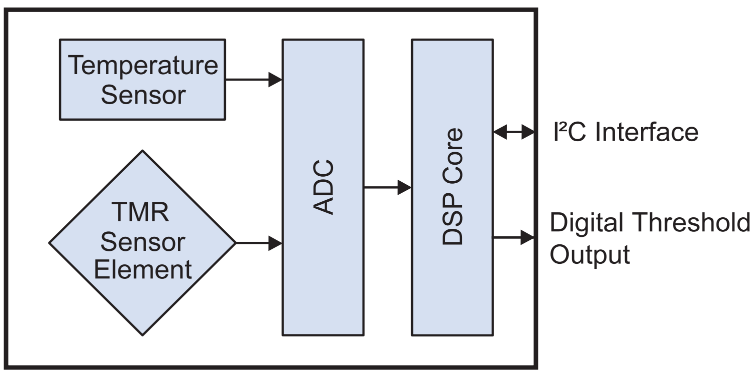
SM223 I^{2}C TMR Smart Magnetometer Sensor



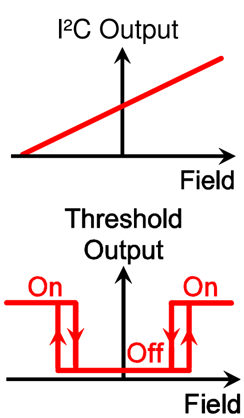
Features

- Analog field measurement
- Digital threshold output
- 3.3 or 5 volt compatible two-wire I^{2}C interface
- Wide 0 to 1.5 mT linear range
- Can detect magnets more than 50 mm away
- Factory calibrated
- Internal temperature compensation
- In-plane sensitivity—more usable than Hall effect
- 2.2 to 3.6 volt supply
- Ultraminiature 2.5 x 2.5 x 0.8 mm TDFN6 package

Simplified Block Diagram



Transfer Functions



Key Specifications

- 10-bit output resolution
- −40°C to +125°C operating range
- 2% FS accuracy for 0 to 125°C
- 15 kSps sample rate for fast response
- 5 mA typical supply current

Applications

- Current sensing
- Proximity sensing
- Automotive applications
- Cylinder position sensing
- Security and intrusion detection

Description

SM223 Smart Sensors provide precise magnetic field measurements and are typically implemented as over-trace current sensors. The sensors combine precise Tunneling Magnetoresistance (TMR) sensor elements with easy-to-use digital signal processing.

The SM223 has an I^{2}C interface that provides magnetic field data and is used to set parameters. A digital comparator output allows programmable thresholds.

Unlike awkward, old-fashioned Hall-effect sensors, TMR is sensitive in-plane for optimal current sensing and easy mechanical interfaces. TMR also provides more sensitivity, higher precision, higher speed, and lower noise than Hall effect sensors.

The device is factory calibrated for high accuracy, and calibration coefficients are stored in internal nonvolatile memory.

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Boundary Ratings

Parameter	Min.	Max.	Units
Supply voltage	−12	4.2	Volts
Input and output voltages (SDA, SCL, and DOUT)	−0.5	V_{CC}+2.5 up to 5.8	Volts
Output current	−100	+100	mA
Storage temperature	−55	150	°C
ESD (Human Body Model)		2000	Volts
Applied magnetic field		Unlimited	Tesla

Operating Specifications (T_{min} to T_{max};2.2<V_{DD}<3.6 V unless otherwise stated)

Parameter	Symbol	Min.	Typ.	Max.	Units	Test Condition
Operating temperature	T_{min}; T_{max}	−40		125	°C	
Supply voltage	V_{DD}	2.2		3.6	V	
Supply current	I_{DD}		5	7	mA	Max. at V_{DD} = 3.6V
Power-on Reset supply voltage	V_{POR}		1.4		V	
Brown-out power supply voltage	V_{BOR}	0.75	1	1.36	V	
Start-up time	T_{STA}		15		ms	
Magnetics						
Linear range		−1.5		1.5	mT (1 mT = 10 Oe in air)	
Resolution	δH		0.001			
Accuracy (% of linear range)				±4	% FS	−40 to 125°C
				±2		0 to 125°C
Precision and Speed						
Digital precision			10		bits	
Update rate			15		kSps	
Magnetic bandwidth			100		kHz	
Start-up time	T_{STA}			15	ms	
Internal Temperature Sensor						
Temperature accuracy (factory calibrated)				±2.5	°C	25 to 85°C
				±5	°C	−40 to 125°C
I²C Interface						
Data transfer rate	DR			400	kBaud	Full duplex
Bus voltage	V_{BUS}	2.2		5.5	V	
Output response and transmission times				20	µs	400 kBaud
Output response and transmission times				20	µs	
Low level input threshold voltage	V_{IL}	0.8			V	
High level input threshold voltage	V_{IH}			2.2	V	V_{OL}=0.4V
Low level output current	I_{OL}	3			mA	
I/O capacitance	$C_{I/O}$			10	pF	
Low level input threshold voltage	V_{IL}	0.8			V	
High level input threshold voltage	V_{IH}			2.2	V	
Low level output current	I_{OL}	3			mA	V_{OL}=0.4V
I/O capacitance	$C_{I/O}$			10	pF	
Package Thermal Characteristics						
Junction-to-ambient thermal resistance	θ_{JA}		320		°C/W	
Package power dissipation			500		mW	

SM223 Overview

Direction of Magnetic Sensitivity

As the magnetic field varies in intensity, the digital output will turn on and off. Unlike Hall effect or other sensors, the direction of sensitivity is in the plane of the package. The diagrams below show current trace and permanent magnet orientations that will activate the sensor in the direction of sensitivity:

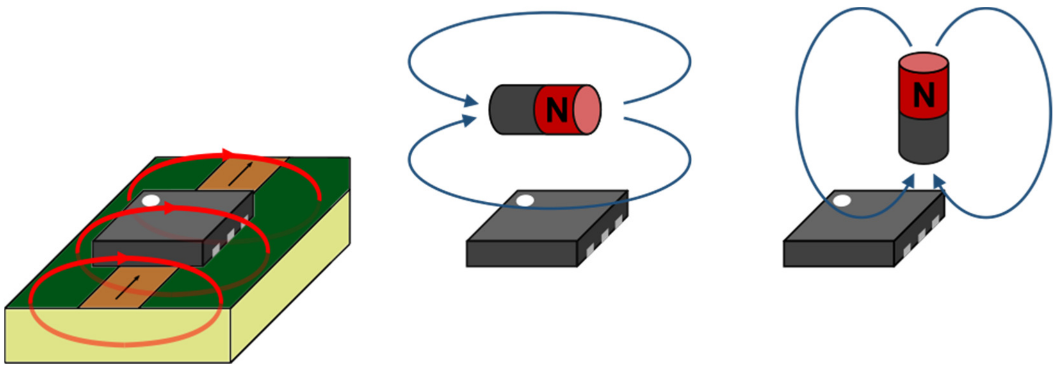

Figure 1. Direction of magnetic sensitivity.

These sensors are bipolar, meaning they can detect the polarity as well as magnitude of magnetic fields.

Typical Operation

Isolated Noncontact Current Sensing

SM223 sensors measure the current through a circuit board trace by detecting the magnetic field generated by the current through the trace. The sensor is ideal for these applications because of the low fields generated. The threshold output can be used for current threshold detection or overcurrent protection.

Typical current sensing configurations are shown below:

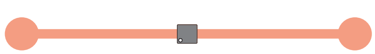

Figure 2a. 0.05" (1.3 mm) trace on top of PCB (0.28 mT/amp; 7 A max. current).

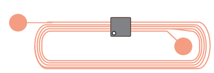

Figure 2b. Five-turn, 0.0055" (0.14 mm) Trace on top of PCB (1.4 mT/amp; 1 A max. current).

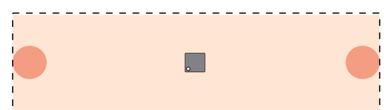

Figure 2c. 0.5" (13 mm) 2 oz. trace on the bottom of 0.062" (1.6 mm) thick PCB (0.03 mT/amp; 50 A max. current).

For the geometry shown below and narrow traces, the magnetic field generated can be approximated by Ampere's law:

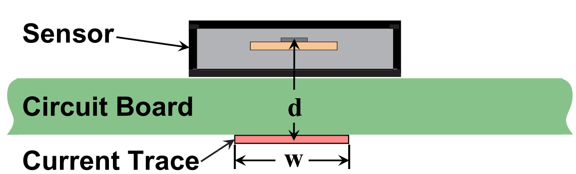

Figure 3. The geometry of current-sensing over a circuit board trace.

$$H = \frac{2I}{d}$$ ["H" in oersteds, "I" in amps, and "d" in millimeters]

For traces on the top side of the board, "d" is simply the distance of the sensor element from the bottom of the package, which is 0.5 millimeters.

Traces on the top side of the board are typically used for currents of five amps or less and low-voltage isolation. Large traces on the bottom side of the PCB can be used for currents of up to 50 to 100 amps with unlimited isolation.

More precise calculations can be made by breaking the trace into a finite element array of thin traces, and calculating the field from each array element. We have a free, Web-based application with a finite-element model to estimate magnetic fields and sensor outputs in this application:

www.nve.com/spec/calculators.php#tabs-Current-Sensing

Position Sensing

A typical proximity sensor using an SM223-10E sensor and magnet is shown below. With a 0.06 mT (0.6 Oe) operate point, the sensor actuates at an airgap of nearly 45 mm (two inches) with a small magnet or 150 mm (six inches) with a large magnet:

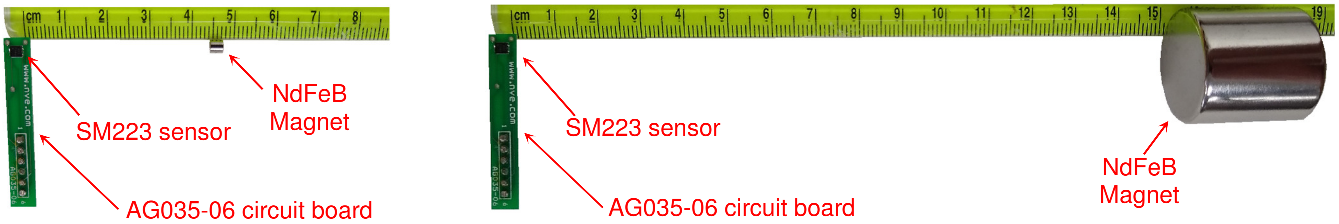

Figure 4. The SM223-10E sensor can be activated by a magnet more than 150 mm away. Maximum sensitivity is in plane with the sensor, with the magnet axis in the pin 2/pin 5 sensor axis. The part is sensitive to either north or south fields.

Cautions for Low Fields

Thresholds even lower than 0.06 mT (0.6 Oe) can be programmed, although care must be taken to account for the earth's magnetic field, which is typically in the 0.05 mT range.

Magnet Distances

Typical magnetic operate distances for the SM223 is illustrated in the following graph with an inexpensive ceramic disk magnet:

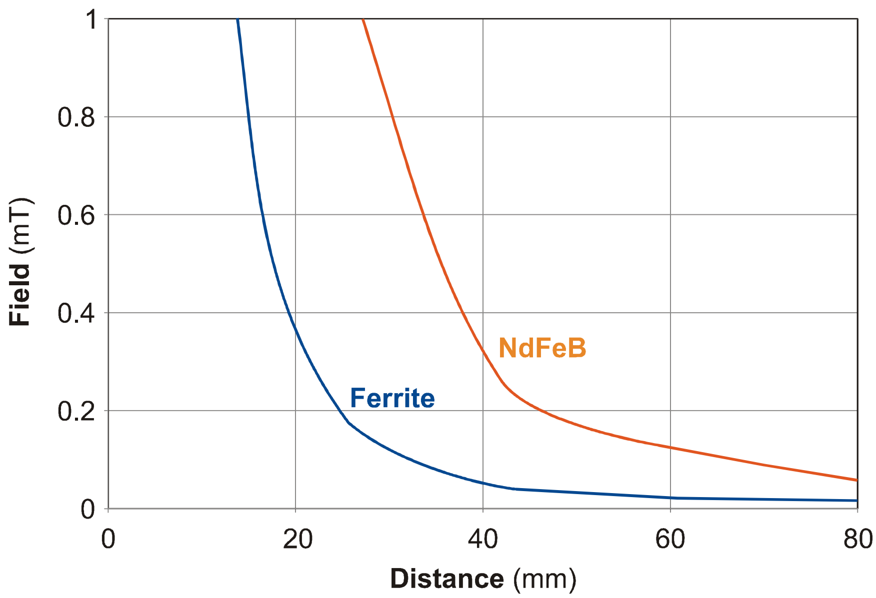

Figure 5. Field vs. distance from the center of the sensor. Ferrite magnet is NVE part number 12216; d=6 mm; t=4 mm; C1/Y10T; Ms=Br=2175 G; NdFeB magnet is N45; d=6 mm; t=4 mm; Ms=Br=13500 G.

Larger and stronger magnets allow farther operate and release distances. For more calculations, use our axial disc magnetic field versus distance web application at:

www.nve.com/spec/calculators.php#tabs-Axial-Disc-Magnet-Field.

SM223 Operation

The SM223 is a high-speed noncontact magnetometer designed for proximity or current sensing. A detailed block diagram is shown below:

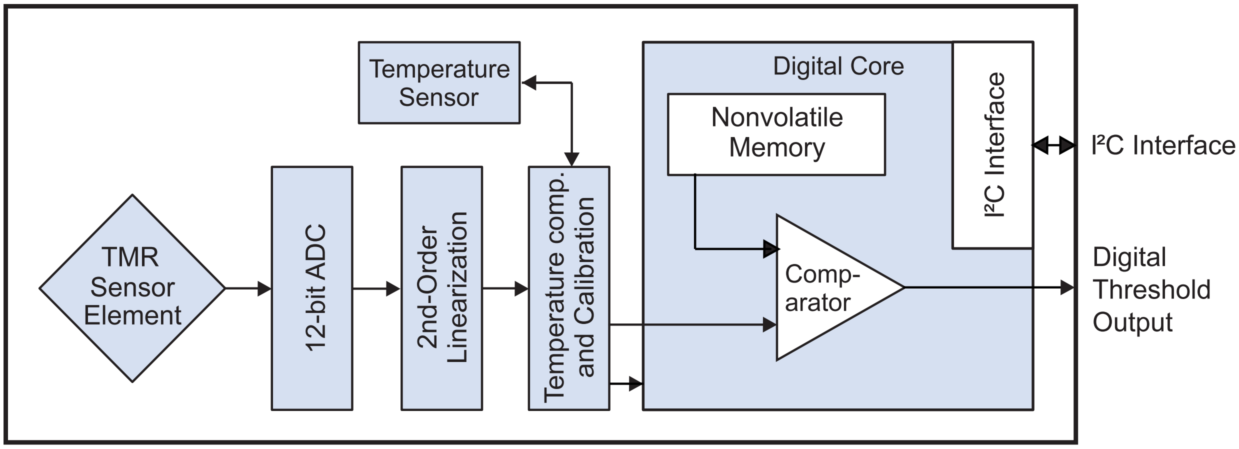

Figure 6. SM223 detailed block diagram.

ADC
The sensor output is digitized with a 12-bit ADC. The device's output precision is 10 bits, and the extra bits ensure computational accuracy.

Digital Filter
A first-order Infinite Impulse Response (IIR) digital filter with a programmable cutoff frequency can be used for ultralow noise if high-frequency operation is required. The cutoff frequency is set by a filter constant, *m,* as follows:

$$f_{CUTOFF}=f_{SAMPLE}/(2\pi m)$$

Where f_{CUTOFF} is the filter cutoff frequency and f_{SAMPLE} is the sensor ADC sampling rate (approximately 15000/s). So for example, if $m = 10$, the cutoff frequency is approximately 300 Hz.

m =1 disables filter so the output is simply updated with each sample. The factory default is the filter turned off.

Sensor Offset
The sensor core of the SM223 is factory calibrated for highest accuracy, and a programmable parameter, sensor_offset, is available for user adjustments to environments with non-zero magnetic fields. sensor_offset is a signed integer.

Internal Temperature Sensor
A factory-calibrated internal temperature sensor compensates for temperature effects, and optionally compensates for temperature effects on permanent magnets. Sensor temperature can also be read via the I²C interface.

Threshold Output
The SM223 has a programmable threshold output. There are two threshold / hysteresis pairs (THRSH1 /HYST1 and THRSH2/HYST2). Normally, the threshold output is high if the field exceeds the threshold, but it can be inverted by setting the "TOUT_invert" bit.

The factory default is an omnipolar threshold output with 1 mT thresholds and 0.1 mT hysteresis:

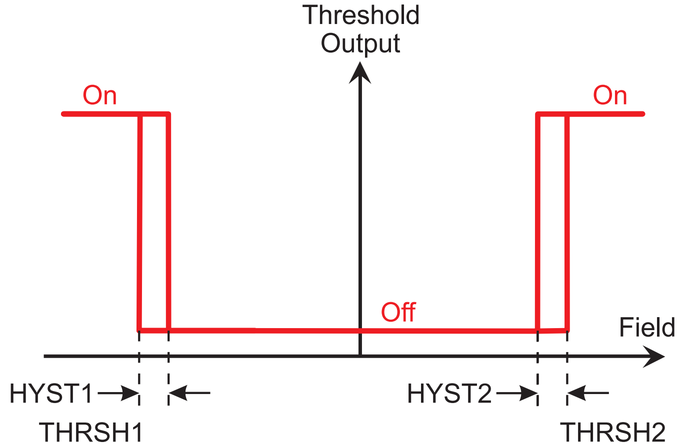

Fig. 7a. Factory default threshold output (THRSH2 = +1 mT; THRSH1 = −1mT; HYST1 = HYST2 = 0.1mT). The output turns on when the field magnitude exceeds the threshold, and operates the same with either magnet pole.

The thresholds can be configured to provide "omnipolar" or "bipolar" responses. Here are two examples of common settings:

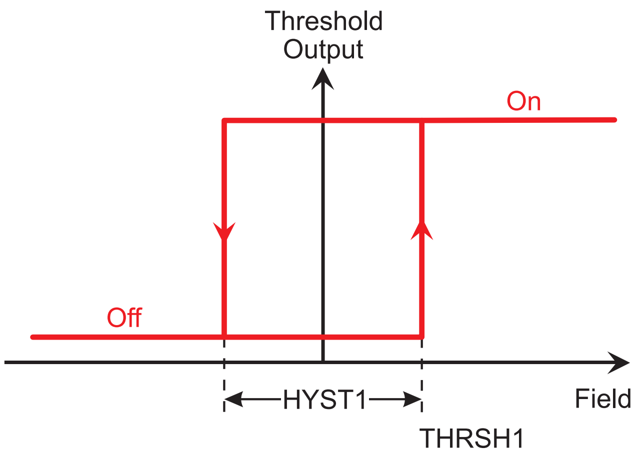

Fig. 7b. "Bipolar" symmetrical threshold output (HYST1 = 2 x THRSH1; THRSH2 not used). The output turns on with a north magnetic pole and off with a south pole.

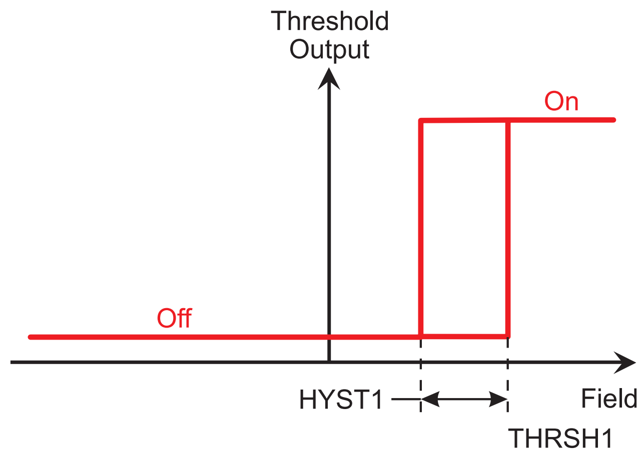

Fig. 7c. "Unipolar" threshold output (HYST1 <THRSH1; THRSH2 not used). The output turns on with a north pole but not with a south pole, and turns off when the field is reduced.

Thresholds parameter constraints are as follows:

- THRSH2 should be greater than THRSH1.
- HYST1 and HYST2 should be positive or zero.
- Unused parameters can be set to 0xFFFF, or set the same as the other parameter.

I²C Interface

Changing the I²C Address in Nonvolatile Memory

The default I²C address is stored in nonvolatile memory, and can be changed like any other parameter. The I²C standard reserves certain addresses, so recommended I²C addresses are 16 to 238 (0x10 to 0xEE hex).

Note that if there are multiple SM223s on the same I²C bus there will be a collision before addresses can be changed. Therefore changing the address in this way may require a single-sensor programming setup.

Overriding the I²C Address with an External Jumper

Grounding the I²C address override pin ("I2CADDR") changes the I²C address to 16 dec regardless of the programmed address. Leaving the pin open or tied HIGH invokes the I²C address in nonvolatile memory, which is 72 dec by default but can be reprogrammed by the user in memory location 0x17. The pin is checked only on power-up.

Eight-Bit I²C Address

In accordance with industry standards, SM223 sensors have eight-bit I²C addresses (seven bits plus an R/W bit). Some I²C Master devices (such as Arduinos) send seven-bit addresses. In this case, the sensor address should be divided by two, so for example a default I²C address of 36 rather than 72 would be used.

Reading and Writing the Sensor Memory

Data is read by first writing an address byte to the sensor (with the I²C Read/Write bit set to "Write"). Subsequent I²C read commands will return the data or parameter in the active address.

On startup the default memory address is 0, which is the calibrated sensor output.

Reading the Sensor

To read the sensor, the master simply writes zero for the address, then reads the two-byte output, which is expressed in thousandths of millitesla. The active address will remain the same until changes, so the output can be read repeatedly without writing the address each time.

Reading and Writing Parameters

Reading and writing parameters are simple three-byte sequences. The master writes a byte for the parameter address, then reads or writes two bytes for the parameter value.

The number of bits in different parameters varies. Unused bits are sent as zeros by the sensor. Similarly, unused bits should be written as zeros to the sensor to avoid an out-of-range parameter that could be ignored.

Because of the slower speed of the sensor's nonvolatile memory, allow 10 ms for parameter writes.

Memory Map

Data and parameter memory addresses are shown in the following table:

	Symbol	Default	Range	Address	Description
Sensor output (calibrated)	Sensor	-	−1500 – +1500	0x00	1500 = 1.5 mT or 15 Oe
Temperature	Temperature	-	−40– 125	0x02	°C
Threshold output	DOUT	-	0 – 1	0x03	
Threshold 1	THRSH1	−1000	−1500– +1500	0x10	1000 = 10 Oe / 1 mT; THRSH2 >THRSH1; HYST1, HYST2 ≥ 0; 0xFFFF to disable
Hysteresis for THRSH1	HYST1	100	−1500 – +1500	0x11	
Threshold2	THRSH2	+1000	−1500 – +1500	0x12	
Hysteresis for THRSH2	HYST2	100	−1500 – +1500	0x13	
Threshold invert	TOUT_invert	0	0 – 1	0x14	HIGH to invert TOUT
Sensor offset	sensor_offset	0	−1500– +1500	0x15	
Digital filter constant	*m*	1	1 – 127	0x16	$f_{CUTOFF} = f_{SAMPLE}/(2\pi\ m)$; f_{SAMPLE} = 15 kSps; *m* = 1 disables filter
I²C address	I2CADDR	72	16 to 238 (0x10 to 0xEE)	0x17	The I²C address with the I2CADDR pin floating or HIGH
Lot code	YY	N/A		0x80	ASCII date code in the form YYWWXX, where: YY = year; WW = work week; XX = internal code. The left-most character is in address 0x80 and the right-most in 0x82.
	WW			0x81	
	XX			0x82	

Table 1. SM223 Memory Locations.

Power-Up and Initialization

All parameters are nonvolatile so they can be set once (via I²C), and remain for the life of the product if desired.

Minimizing Magnetic Interference

Several precautions can be taken for applications requiring the best accuracy:

- Components such as resistors and capacitors are generally slightly magnetic, and should be located at least several millimeters from the sensor. Such components should not be placed between magnet and the sensor.
- If components must be located near the sensor, ultrasmall components such as 0201 (0603 metric) contain less ferromagnetic material than larger components.
- Nonmagnetic resistors and capacitors can be used for extremely sensitive applications. A nonmagnetic 0.1 µF bypass capacitor can be used close the sensor, with a conventional 10 µF ceramic capacitor at least several millimeters away.

Minimizing Noise

Several steps minimize noise:

- Inadequate bypassing can cause noise or anomalous device behavior. 10 µF total bypass capacitance is recommended. To minimize magnetic field disruption, a small (e.g., 0201 / 0603 metric) 0.1 µF ceramic capacitor can be placed as close as possible to the V_{DD} and GND pins. The small capacitors contain very little ferromagnetic material. An additional 10 µF ceramic capacitor is also recommended, placed a few millimeters away so that it does not magnetically interfere with the sensor.
- Use a circuit board ground plane.
- If the sensor is not being used for current over trace sensing, ground the sensor's center pad so the leadframe acts as a shield.

Applications

Typical Microcontrollers Interface

A typical microcontroller interface is shown below:

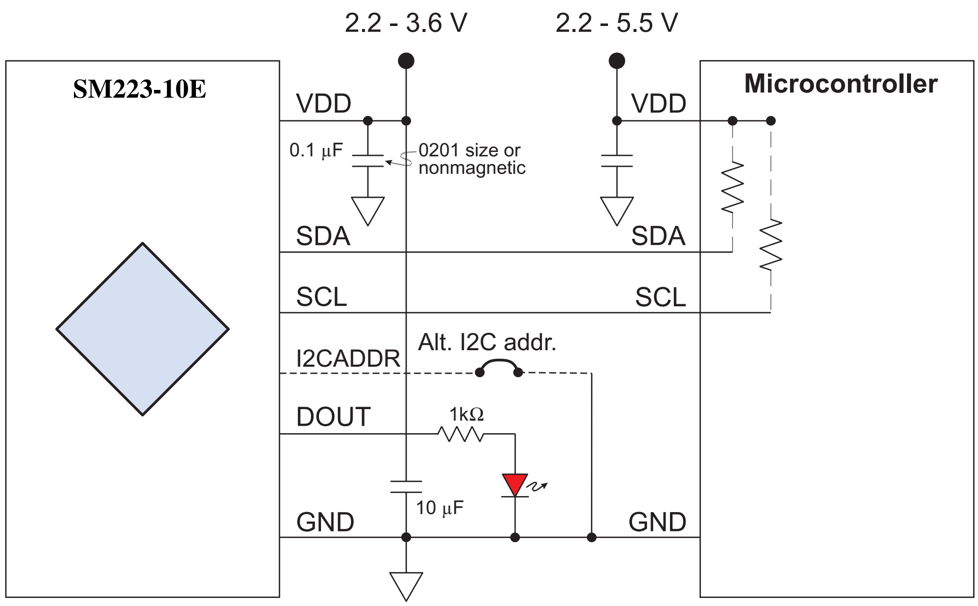

Figure 8. Typical microcontroller interface.

The SM223 is configured as a Slave and the microcontroller should be configured as the Master. The SM223 I²C interface is compatible with a 3.3V or 5Vbus.

The SCL and SDA lines are open-drain, so the microcontroller's internal pull-up resistors should be activated in software. External resistors can be used to maximize rise time for high-speed I²C operation, or to preserve I²C speed if there are multiple slaves or a multi-master configuration adding bus capacitance. If external pull-ups are used with different power supplies, they should be connected to the lower supply voltage. A typical external pull-up resistor value is 10 kΩ. If I²C speed is not critical, the effects of bus capacitance can be overcome by slowing the I²C speed.

The I2CADDRpin can be left unconnected for the default I²C address (72 decimal/0x48 hex), or the pin can be ground to select an alternate address (16 decimal/0x10 hex).

An LED can be used to indicate the digital output. The appropriate series resistor depends on the supply voltage and LED type. A high-efficiency LED will operate over the sensor's entire 2.2 to 3.6V supply range with the 1 KΩ resistor, although its brightness will change with the supply voltage.

Overcurrent Protection

An SM223 digital output can be used as a "virtual circuit breaker" for overcurrent protection of a load such as a DC motor:

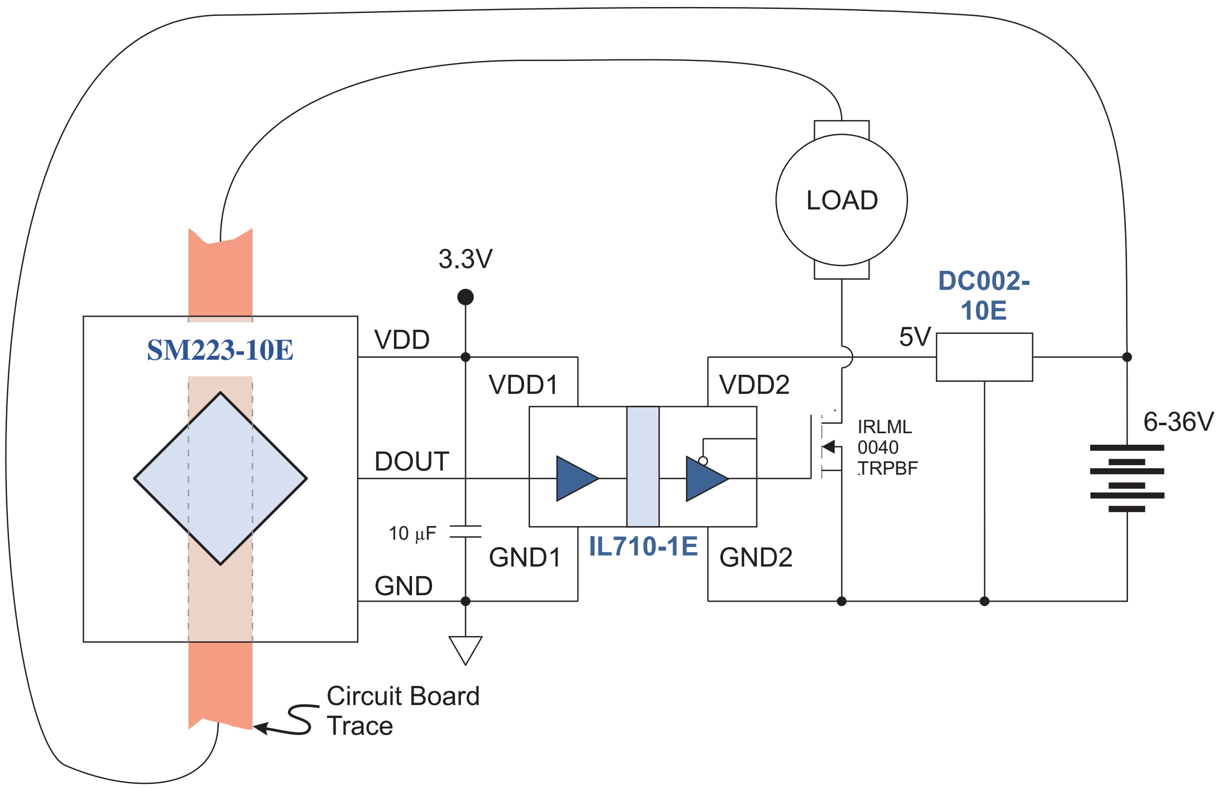

Figure 9. Typical overcurrent protection circuit.

The IL710-1E is an ultraminiature (MSOP8) data coupler that isolates the controller power from the load power. The DC002-10E is a high-voltage tolerant, five-volt regulator to power the gate drive. The power MOSFET has 4.5 volt drive voltage and 3.6 amp and 40 volt drain-to-source voltage capability. The sensor is located over a trace that carries current to the motor.

In this configuration, DOUT_invert is set to 1 to invert DOUT so that the output goes LOW for overcurrent. Typical values are THRSH1 = −100 (dec); THRSH2 = +100; HYST1 = HYST2 = 200. Setting the hysteresis to the difference in the thresholds causes DOUT to latch ON if the current exceeds the threshold. The output can then be reset by via I²C or by cycling the sensor power.

If the field generated by the motor current exceeds the threshold, DOUT goes LOW, the isolator output also goes LOW, the MOSFET turns off, and power is removed from the load.

The SM223's high sample rate ensures rapid detection of an overcurrent condition. But unlike shunt resistor-based circuits, there are virtually no losses associated with current sensing, and the controller can be electrically isolated from the motor for less noise and more safety.

An SM223 can also drive solid-state relays rather than the isolator and MOSFET in Figure 9. Relays are normally connected from DOUT to VDD to take advantage of the output's high output sink capability. Relays with a three-volt "Must Turn On Voltage" and fairly high input impedance can be driven directly by the sensor output.

Reciprocating Actuator
A back-and-forth actuator can be constructed with just a single SM223 smart sensor, one magnet. No microprocessors are needed. The sensor's digital threshold output is connected to the direction input of a stepper motor driver board, so the actuator motor reverses as the sensor turns on and off:

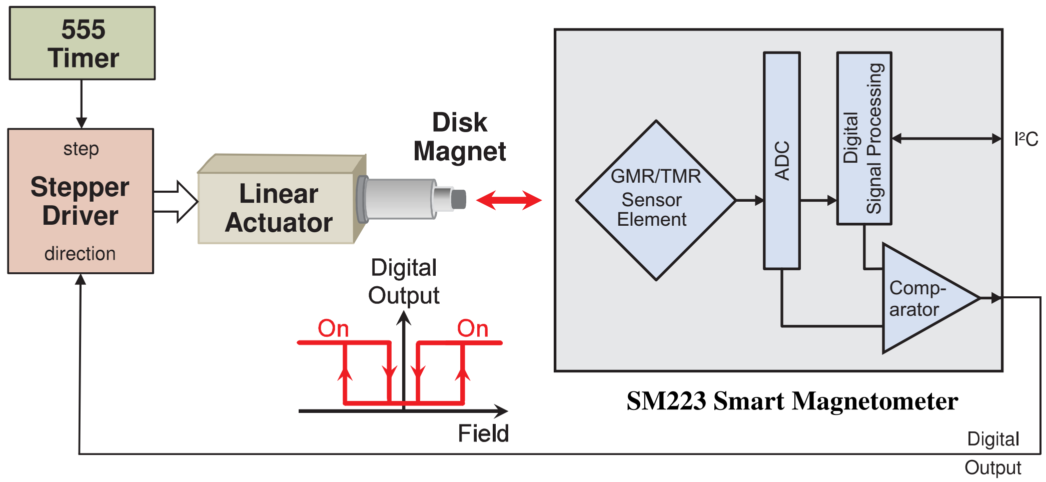

Figure 10. Reciprocating actuator using an SM223 smart sensor.

The flexibility and wide range of the sensor's digital threshold output makes it ideal for this application. For example, a 1 mT turn-on threshold with 0.9 mT hysteresis provides a 0.1 mT turn-off threshold and a distance of more than one inch (25 mm) between the turn-on and turn-off thresholds using a small rare-earth magnet. Using symmetrical thresholds ensures the control works with either magnet polarity.

The programmed thresholds are nonvolatile, so the sensor can be programmed once and then operated without a computer or microprocessor interface.

Illustrative Arduino / Trinket Code to Read Sensor Output Continuously

```
/*************************************************************************************
Trinket displays NVE SM223 I²C Smart Magnetometer on a COM-11441 7-segment display
SDA=#0; SCL=#2; LED=#1; USB for programming=#3/#4
*************************************************************************************/
#include <TinyWireM.h> //ATTiny85 I²C Master library
//Use Wire.h for Arduino and replace "TinyWireM." with "Wire."
int sensor, digit; //Sensor output; digit counter
void setup() {TinyWireM.begin();}

void loop() {
TinyWireM.requestFrom(36,2); //Request two bytes from I²C address 72 (36 = 72/2)
  sensor = TinyWireM.read()<<8; //Read sensor MSB
  sensor|=TinyWireM.read(); //Read sensor LSB

//Display sensor output
TinyWireM.beginTransmission(0x71); //Write to 7-segment display (I²C address 0x71)
TinyWireM.write(0x76); //Clear display
TinyWireM.write(0x77); //Set decimal point
TinyWireM.write(0b001); //Displays xx.xx mT
for(digit=1000; digit>0; digit/=10) { //Start at 1000s digit
TinyWireM.write((sensor%(digit*10))/digit); //Scan through display digits
  }
TinyWireM.endTransmission();
delay(100); //10 samples/second
}
```

Illustrative Arduino / Trinket Code to Set Digital Output Thresholds

```
/*************************************************************************************
Sets SM223 thresholds and hysteresis via I²C.
Trinket connections: SDA=#0; SCL=#2; LED=#1; USB for programming=#3/#4
*************************************************************************************/
#include <TinyWireM.h> //ATTiny85 I²C Master library
//Use Wire.h for Arduino and replace "TinyWireM." with "Wire."
Int sensor;//Sensor reading
Char addr; //Sensor memory address
Const int parameter[] = {//Sensor parameters starting at address0x30:
 -1000, //Threshold 1 (-10 Oe / -1 mT)
 100,   //Hysteresis for Threshold 1 (1 Oe / 0.1mT)
1000,//Threshold 2 (10 Oe / 1 mT)
100 //Hysteresis for Threshold 2 (1 Oe / 0.1mT)
};

void setup() {
TinyWireM.begin();
for(addr=0x10; addr<= 0x13; addr++){ //Threshold and hysteresis memory addresses

//Write address
TinyWireM.write(addr); // Address

//Write parameter to sensor
TinyWireM.write(parameter[addr-0x10]>>8); //parameter MSB
TinyWireM.write(parameter[addr-0x10]&0xFF); //parameter LSB
delay (10); //Delay 10 ms to allow writing to nonvolatile memory

}//Next address
```

Evaluation Support

Breakout Board

The AG975 breakout board provides easy connections to an SM223-10E sensor with a six-pin connector. It also has the recommended 10 µF bypass capacitor:

Figure 11. AG975 breakout board (actual size)
0.5" x 0.6" (12 mm x 15 mm)

Evaluation Kit

This simple evaluation board includes an SM223-10E Smart Magnetometer and a microcontroller that interfaces to the SM223 via I²C and to a PC via USB.

The sensor can be activated with a magnet or an on-board current trace. A Windows-based user interface provides two-way communication with the sensor to display the sensor outputs and change sensor programmable parameters. A microcontroller PWM output on the board provides an analog representation of the measured field.

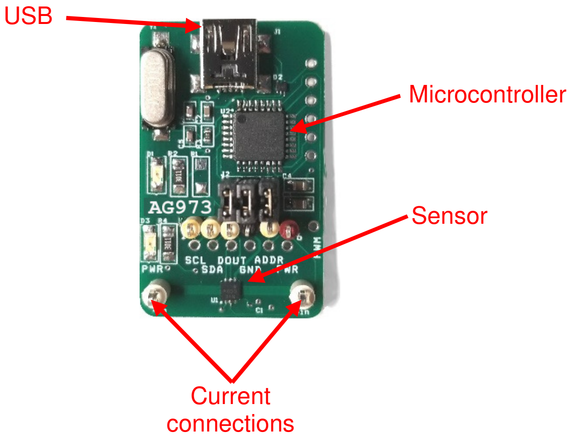

Figure 12. AG973: SM223 Smart Magnetometer Evaluation board
1" x 1.625" (25 mm x 41 mm)(actual size)

Socket Board

The AG954-07E provides a TDFN6 socket for easy interface to smart sensors such as the SM223-10E without soldering:

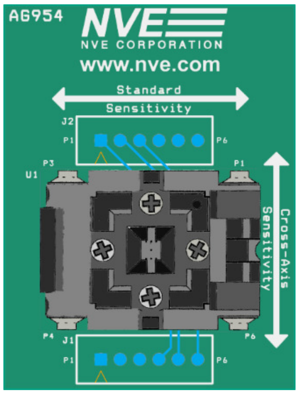

Figure 13. AG954-07E: TDFN socket board
1.5" x 2" (38 mm x 50 mm)(actual size)

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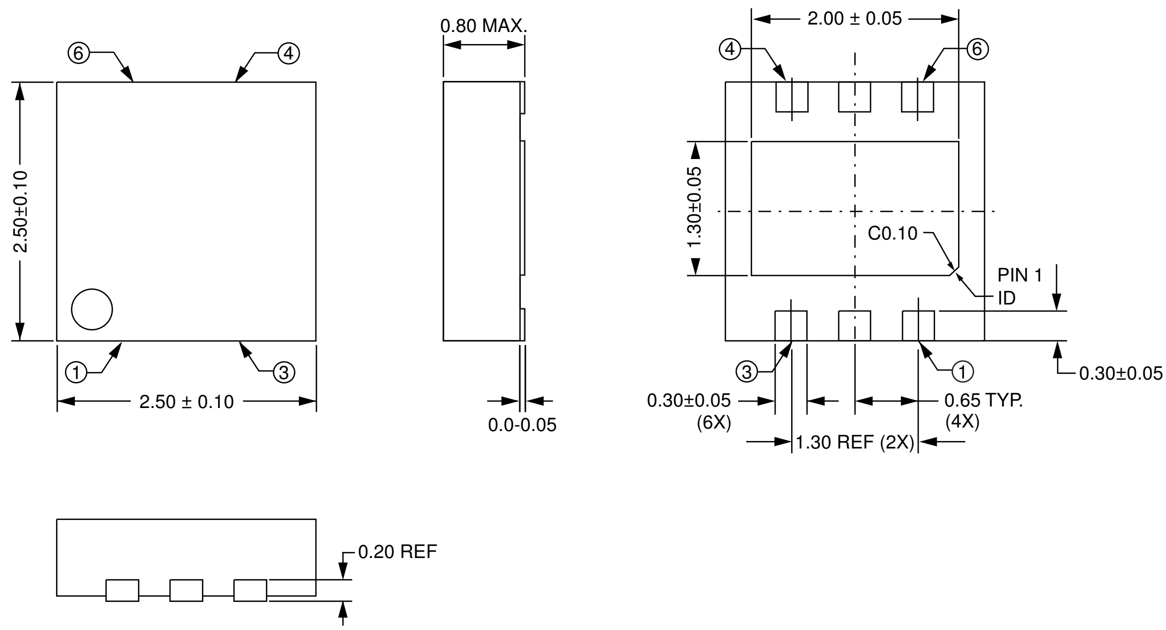
2.5 x 2.5 mm TDFN6 Package



Pad	Symbol	Description
1	DOUT	Digital Output (CMOS output; default HIGH if field is above threshold)
2	I2CADDR	I²C address override (LOW-true input; read on power-up). Grounding this pin changes the I²C address to 16 dec regardless of the programmed address. Open or HIGH invokes the I²C address in nonvolatile memory.
3	GND	Ground/V_{SS}
4	VDD	Power Supply (bypass with a 10 µF capacitor)
5	SDA	I²C Data (bidirectional; open drain)
6	SCL	I²C Clock (input)
Center pad		Internal leadframe connection; connect to GND to minimize noise.

Notes:

- Dimensions in millimeters.
- Soldering profile per JEDEC J-STD-020C, MSL 1.

RoHS COMPLIANT

Ordering Information

SM223 - 10E TR13

Product Family

SM = Product Family (Smart Magnetometers)

Base Part Number

2 = TMR element with 2-byte data

2 = Magnetic Orientation (cross-axis, i.e., sensitive to a field vector in the pin 2 / pin 5 direction)

3= I^2C Interface; Magnetic Field Linear Range 0 to 1.5 mT

Part Package

10E = RoHS-Compliant 2.5 x 2.5 mm TDFN6 Package

Bulk Packaging

TR13 = 13" Tape and Reel Package

Available Product Variants

Part Number	Linear Range	Accuracy	Interface	Breakout Board	Evaluation Kit
SM225-10E	0 to 15 mT	±2%	SPI	AG959-07E	AG953-07E
SM223-10E	0 to 1.5 mT	±2%	I^2C; Digital Threshold	AG975-07E	AG973-07E
SM228-10E	0 to 15 mT	±2%		AG968-07E	AG969-07E
SM124-10E	0 to 1 mT	±5%		AG958-07E	AG952-07E
SM125-10E	0 to 4mT	±5%		AG961-07E	AG962-07E

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Revision History

SB-00-142-RevA
March 2022

Change

- Initial release.

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